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## SOIL MANAGEMENT

# Tillage and Nitrogen Fertilization Influence Grain and Soil Nitrogen in an Annual Cropping System

Ardell D. Halvorson,* Brian J. Wienhold, and Alfred L. Black


## ABSTRACT

**Increasing the frequency of cropping in dryland systems in the northern Great Plains requires the application of N fertilizer to maintain optimum crop yields. A 12-yr annual cropping rotation [spring wheat (*Triticum aestivum* L.)–winter wheat–sunflower (*Helianthus annuus* L.)] under dryland conditions was monitored to determine the influence of tillage system [conventional till (CT), minimum till (MT), and no till (NT)] and N fertilizer rate (34, 67, and 101 kg N $ha^{-1}$) on N removed in grain and annual changes in postharvest soil $NO_3$–N. Nitrogen removal in the grain increased with increasing N rate in most years. Total grain N removal was lowest with NT at the lowest N rate and highest with NT at the highest N rate compared with CT. Total grain N removal after 12 cropping seasons was 144, 84, and 61% of the total N applied for the 34, 67, and 101 kg N $ha^{-1}$ fertilizer rates, respectively. Residual soil $NO_3$–N levels were not affected by N rate or tillage system in the first 3 yr, but they increased significantly following consecutive drought years. Residual $NO_3$–N in the 150-cm soil profile tended to be higher with CT and MT than with NT. Soil $NO_3$–N movement below the crop root zone may have occurred in 1 or 2 yr when precipitation was above average. Results indicate that NT, with annual cropping, may reduce the quantity of residual soil $NO_3$–N available for leaching compared with MT and CT systems.**


No-till (NT) and minimum till (MT) systems have allowed producers in the semiarid Great Plains to intensify the frequency of cropping compared with the traditional crop–fallow system. Deibert et al. (1986) and Peterson et al. (1996) point out that more continuous cropping is needed in the Great Plains to attain more efficient use of limited water supplies. Increasing the frequency of cropping to 2 out of 3 yr, 3 out of 4 yr, or even to every year has been successful when reduced tillage systems are used (Aase and Schaefer, 1996; Farahani et al., 1998; Halvorson, 1990; Halvorson and Reule, 1994; Halvorson et al., 1999a, 1999b, 2000).

Halvorson and Black (1985) reported annual crop yields that were generally >80% of 2-yr spring wheat (SW)–fallow yields when grown in an annual cropping system with adequate N and P fertilization. Halvorson and Reule (1994) showed that N fertilization is needed to optimize crop yields in a dryland annual cropping system. Long-term N fertility studies have shown that residual soil $NO_3$–N levels increase when N fertilization rates exceeded that needed for maximum yield (Halvorson and Reule, 1994; Porter et al., 1996; Raun and Johnson, 1995; Westerman et al., 1994). Black et al. (1981) reported more efficient water use with more intensive cropping systems and increased yields with N fertilization. In addition to more efficient water use, more intensive MT and NT cropping systems have the potential to be more profitable and reduce soil erosion potential (Dhuyvetter et al., 1996; Merrill et al., 1999).

Long-term applications of N fertilizer to dryland cropping systems can influence the level of residual soil $NO_3$–N in the profile. Increasing levels of residual soil $NO_3$–N in the lower part of the root zone increases the potential of leaching $NO_3$–N below the root zone and into shallow water tables, creating environmental concerns (Keeney and Follett, 1991; Peterson and Power, 1991). Information is limited on the effects of tillage system and long-term N fertilizer application on soil $NO_3$–N levels in annual cropping systems in the northern Great Plains (Campbell et al., 1993). Halvorson et al. (1999a, 1999b, 2000) reported the long-term influence of tillage and N fertilization on SW, winter wheat (WW), and sunflower (SF) grain yields within a SW–WW–SF cropping system. This phase of the study evaluated the influence of tillage system and N fertilizer rate on grain N removal and postharvest residual soil $NO_3$–N within this SW–WW–SF cropping system over 12 yr.

## MATERIALS AND METHODS

The study was initiated in 1984 on a Temvik–Wilton silt loam soil (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls) located near Mandan, ND. An annual cropping rotation, SW–WW–SF, was managed under three tillage systems: Conventional till (CT), MT, and NT (Halvorson et al., 1999a, 1999b, 2000). Hard red wheat and oil sunflower were grown in this study. Nitrogen fertilizer was applied in early spring each year to each crop as a broadcast application of ammonium nitrate ($NH_4NO_3$) at rates of 34, 67, and 101 kg N $ha^{-1}$, except for 1991 and 1992 when no N was applied because of a buildup of residual soil $NO_3$–N due to drought conditions and low yields from 1988 through 1990. Data collection was from 1985 through 1996, which represented four complete cycles through the rotation. The total quantity of N applied during the 12 yr was 336, 672, and 1008

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**Abbreviations:** CT, conventional till; MT, minimum till; NT, no till; SF, sunflower; SW, spring wheat; WW, winter wheat.



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kg N ha$^{-1}$ for the 34, 67, and 101 kg N ha$^{-1}$ treatments, respectively.

Each main block of the study was 137.2 by 73.1 m. Tillage plots (45.7 by 73.1 m) were oriented in a north–south direction, and N plots (137.2 by 24.4 m) were oriented in an east–west direction across all tillage plots. Triplicate sets of plots (SW–WW–SF, WW–SF–SW, and SF–SW–WW crop sequences) were established to allow all phases of the rotation to be present each year. The experimental design was a strip-split plot with tillage and N rate treatments stripped with three replications. The grain yields and production details have been reported by Halvorson et al. (1999a, 1999b, 2000). Annual grain yields and grain N removal present here are the average of the SW, WW, and SF crops grown in the triplicate sets of plots each year. This was done to obtain an overall response of the SW–WW–SF cropping system to tillage and N treatments.

Grain samples collected at harvest of each crop each year were analyzed for N content using a wet acid digest procedure (Lachat Instruments, 1992). Samples were ground to pass a 20 mesh screen before analysis. In 1994 and 1996, grain N was determined by dry combustion with a Carlo-Erba[1] C-N analyzer (Schepers et al., 1989). The total amount of grain N removed from the cropping system each year was determined.

Soil samples, one 3-cm-diam. core per plot, were collected from each tillage and N fertilizer treatment following harvest of each crop each fall. Samples were collected in 30-cm increments to a depth of 150 cm. Soil $NO_3$–N was determined by Cd reduction with an autoanalyzer (Lachat Instruments, 1989; Technicon Ind. Syst., 1973) on a 5:1 extract/soil ratio using 2 *M* KCl extracting solution from 1985 to 1993 and a 0.01 *M* calcium sulfate ($CaSO_4$) extracting solution from 1993 through 1996. Analysis of laboratory check soil samples indicated that both extraction methods and analyzers resulted in similar soil $NO_3$–N values. Annual postharvest soil $NO_3$–N data presented in this paper represents an average of the three crop sequences (SW, WW, and SF) grown on the triplicate set of plots used in the study each year.

Precipitation was measured with a recording rain gauge at the site from April through October each year. November through March precipitation was estimated from the U.S. Weather Bureau measurements made at the Northern Great Plains Research Laboratory at Mandan, ND, located approximately 5 km northeast of the site.

Analysis of variance procedures were conducted using SAS statistical procedures (SAS Inst., 1991) with years treated as a fixed variable. All differences discussed are significant at $P = 0.05$ unless otherwise stated. An LSD was calculated only when the analysis of variance $F$ test was significant at $P \leq 0.05$.

[1] Trade names and company names are included for the benefit of the reader and do not imply endorsement or preferential treatment of the product by USDA-ARS.

# RESULTS

## Precipitation

Annual precipitation from 1984 through 1996 varied from a low of 205 mm in 1988 to a high of 659 mm in 1993 (Table 1). The average annual precipitation during the study at the research site was 418 mm, slightly more than the 82-yr average of 409 mm at the Northern Great Plains Research Laboratory, Mandan, ND. Monthly precipitation deviated greatly from the 13-yr average monthly precipitation. Three consecutive years, 1988–1990, were droughty with reduced grain yields (Halvorson et al., 1999a, 1999b, 2000). Annual precipitation in 1986, 1993, 1994, and 1995 was above average (Table 1).

## Grain Yield

The individual grain yield data for each crop for the 12 yr of the study were previously reported (Halvorson et al., 1999a, 1999b, 2000). Annualized grain yields for the rotation are reported in Table 2 but will not be a major topic of discussion here. The tillage × N rate × year interaction was significant for grain yield. Grain yields during the first 6 yr of the study showed little response to N fertilization, except in 1986 and 1987, for all tillage treatments. Following the drought years (1988–1990), response to N rate was minimal in 1991 and 1992 due to high levels of residual soil $NO_3$–N in the profile. From 1993 through 1996, grain yield response to N fertilization was minimal within the CT plots, and grain yields were generally maximized with 67 kg N ha$^{-1}$ within the MT plots and maximized at the highest N rate within the NT plots. Grain yield response to tillage treatment varied from year to year and with N rate.

## Grain Nitrogen Removal

The annual removal of grain N varied with tillage system, N fertilizer rate, and year (Table 3). Grain N removal generally increased with increasing N rate each year for all tillage treatments, except in 1988 and 1989 when drought limited grain yields. Grain N removal

**Table 1. Monthly and annual precipitation at the research site southwest of Mandan, ND.**

| Year | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mm | | | | | | | | | | | | |
| 1984 | 10 | 5 | 31 | 87 | 7 | 89 | 17 | 12 | 14 | 32 | 14 | 9 | 326 |
| 1985 | 2 | 0 | 6 | 36 | 159 | 38 | 23 | 94 | 33 | 28 | 22 | 7 | 448 |
| 1986 | 9 | 5 | 4 | 77 | 60 | 58 | 176 | 48 | 108 | 5 | 71 | 0 | 622 |
| 1987 | 2 | 3 | 36 | 0 | 89 | 27 | 95 | 99 | 1 | 1 | 0 | 2 | 355 |
| 1988 | 5 | 10 | 16 | 0 | 20 | 37 | 5 | 69 | 14 | 4 | 10 | 15 | 205 |
| 1989 | 13 | 2 | 3 | 57 | 46 | 18 | 33 | 38 | 27 | 3 | 10 | 6 | 256 |
| 1990 | 6 | 3 | 8 | 53 | 143 | 34 | 0 | 0 | 5 | 32 | 0 | 4 | 290 |
| 1991 | 0 | 1 | 10 | 40 | 61 | 85 | 34 | 16 | 58 | 33 | 9 | 0 | 346 |
| 1992 | 4 | 7 | 13 | 7 | 39 | 99 | 104 | 36 | 17 | 5 | 21 | 9 | 360 |
| 1993 | 1 | 10 | 4 | 31 | 63 | 124 | 348 | 36 | 2 | 1 | 26 | 13 | 659 |
| 1994 | 9 | 11 | 20 | 36 | 21 | 76 | 40 | 6 | 147 | 129 | 30 | 8 | 533 |
| 1995 | 14 | 6 | 29 | 46 | 138 | 36 | 170 | 50 | 28 | 19 | 5 | 9 | 548 |
| 1996 | 22 | 6 | 22 | 8 | 55 | 86 | 81 | 41 | 76 | 31 | 40 | 12 | 481 |
| Avg. | 7 | 5 | 16 | 37 | 69 | 62 | 87 | 42 | 41 | 25 | 20 | 7 | 418 |

**Table 2. Annualized grain yields as a function of tillage and N treatment, averaged over three crops [spring wheat (SW), winter wheat (WW), and sunflower (SF)] grown in SW–WW–SF rotation at Mandan, ND (significant tillage × N rate × year interaction).**

| Tillage† | N rate | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | | | | | | | | |
| CT | 34 | 2012‡ | 1888 | 1789 | 417 | 592 | 751 | 1071 | 2237 | 1704 | 2044 | 1790 | 1653 | 1496 |
| | 67 | 2039 | 2193 | 2000 | 431 | 583 | 709 | 1104 | 2162 | 2041 | 2064 | 2012 | 1561 | 1575 |
| | 101 | 2014 | 2528 | 2033 | 432 | 535 | 759 | 1084 | 2268 | 1899 | 2084 | 2010 | 1668 | 1610 |
| MT | 34 | 2087 | 1919 | 1990 | 448 | 693 | 737 | 1232 | 2596 | 1771 | 2198 | 1815 | 1773 | 1605 |
| | 67 | 2211 | 2262 | 2253 | 478 | 761 | 858 | 1233 | 2326 | 2099 | 2292 | 1980 | 1814 | 1714 |
| | 101 | 2052 | 2566 | 2158 | 502 | 650 | 858 | 1242 | 2661 | 2086 | 2389 | 2067 | 1896 | 1761 |
| NT | 34 | 2286 | 1706 | 1989 | 366 | 862 | 880 | 1330 | 2345 | 1512 | 1850 | 1277 | 1742 | 1512 |
| | 67 | 2396 | 1984 | 2257 | 420 | 814 | 983 | 1253 | 2330 | 1970 | 2093 | 1596 | 2081 | 1681 |
| | 101 | 2392 | 2301 | 2361 | 442 | 911 | 967 | 1380 | 2830 | 2043 | 2223 | 1768 | 2289 | 1826 |

† CT, conventional till; MT, minimum till; NT, no till.
‡ $LSD_{(0.05)}$ = 155 kg ha$^{-1}$ (compare tillage within N rate × year); 144 kg ha$^{-1}$ (compare N rates within tillage × year); 393 kg ha$^{-1}$ (compare years within tillage × N rate).

varied from year to year within tillage treatments. In general, grain N removal with NT was less than that with CT and MT at the 34 kg N ha$^{-1}$ rate in 1986, 1988, 1992, 1993, 1994, and 1995. With the 67 kg N ha$^{-1}$ rate, grain N removal with NT equaled or exceeded that with CT in 7 yr and was less than CT in 5 yr. At the 101 kg N ha$^{-1}$ rate, grain N removal with NT exceeded that of CT in 7 yr, equaled CT in 4 yr, and was less than CT in 1 yr.

The tillage × N rate interaction was significant for the total N removed in the grain after 12 crop years (Table 4). At the 34 and 67 kg N ha$^{-1}$ rates, grain N removal was greatest with MT compared with CT and NT. At the 101 kg N ha$^{-1}$ rate, grain N removal was greater with NT and MT than with CT.

The total quantity of grain N removed in 12 crop seasons exceeded that applied as fertilizer at the 34 kg N ha$^{-1}$ rate and was less than that applied at the 67 and 101 kg N ha$^{-1}$ rates. Averaged across all tillage treatments, grain N removal was 144, 84, and 61% of the total applied N for the 34, 67, and 101 kg N ha$^{-1}$ rates, respectively. Thus, more N was being applied to the system at the two highest N rates than was being removed in the grain. At 34 kg N ha$^{-1}$, grain N removal was 144, 153, and 134% of the total applied N for the CT, MT, and NT treatments, respectively. At 67 kg N ha$^{-1}$, grain N removal was 82, 88, and 82% of the total applied N for the CT, MT, and NT treatments, respectively, and at 101 kg N ha$^{-1}$, it was 58, 63, 63%, respectively.

## Soil Nitrate-Nitrogen Accumulation and Distribution

Postharvest $NO_3$–N (average of all crop sequences) in the 0- to 150-cm profile varied with tillage system, N fertilizer rate, and year (Table 5) for the SW–WW–SF rotation. Postharvest soil $NO_3$–N generally increased with increasing N rate for all tillage treatments and years, with the exception of 1985 and 1986. During the drought years of 1988 through 1990, residual soil $NO_3$–N in the 150-cm profile increased for all tillage and N treatments. This reflects the low level of grain N removal in these years and the fact that the fertilizer N applied to the crop in 1988 and 1989 was positionally unavailable to the crop due to minimal effective precipitation (Table 1) to move the fertilizer N into the root zone. Postharvest $NO_3$–N levels (Table 6) were elevated in the 0- to 30-cm soil depth from 1988 through 1991. The accumulation of $NO_3$–N in the 150-cm soil profile was greater with the CT and MT treatments than with NT (Table 5). This probably reflects the effects of tillage in increasing the amount of N mineralized in the CT and MT plots. Wienhold and Halvorson (1998) showed that NT had a higher level of total soil N in the surface 15 cm of soil than MT and CT treatments after 10 crop years

**Table 3. Annualized grain N removal as a function of tillage and N treatment, averaged over three crops [spring wheat (SW), winter wheat (WW), and sunflower (SF)] grown in SW–WW–SF rotation at Mandan, ND (significant tillage × N rate × year interaction).**

| Tillage† | N rate | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg N ha$^{-1}$ | | | | | | | | | | | |
| CT | 34 | 49‡ | 45 | 45 | 14 | 24 | 33 | 39 | 60 | 44 | 47 | 45 | 42 |
| | 67 | 59 | 58 | 55 | 14 | 23 | 31 | 43 | 60 | 56 | 52 | 53 | 45 |
| | 101 | 63 | 69 | 62 | 14 | 23 | 33 | 43 | 68 | 52 | 55 | 52 | 49 |
| MT | 34 | 51 | 46 | 52 | 14 | 25 | 30 | 43 | 68 | 44 | 48 | 47 | 45 |
| | 67 | 63 | 58 | 62 | 15 | 28 | 35 | 47 | 65 | 57 | 56 | 53 | 51 |
| | 101 | 66 | 73 | 66 | 17 | 26 | 36 | 49 | 77 | 57 | 61 | 56 | 55 |
| NT | 34 | 50 | 38 | 47 | 10 | 30 | 34 | 43 | 53 | 33 | 37 | 36 | 39 |
| | 67 | 64 | 49 | 59 | 12 | 30 | 40 | 44 | 57 | 46 | 46 | 45 | 56 |
| | 101 | 70 | 61 | 70 | 14 | 34 | 40 | 53 | 74 | 51 | 54 | 50 | 65 |

† CT, conventional till; MT, minimum till; NT, no till.
‡ $LSD_{(0.05)}$ = 4 kg N ha$^{-1}$ (compare tillage within N rate × year); 4 kg N ha$^{-1}$ (compare N rates within tillage × year); 5 kg N ha$^{-1}$ (compare years within tillage × N rate).

**Table 4. Total N removed in grain after 12 crop years as a function of tillage and N treatments, averaged over three crops [spring wheat (SW), winter wheat (WW), and sunflower (SF)] grown in SW–WW–SF rotation from 1985 to 1996. (Significant tillage × N rate interaction).**

| Tillage† | N rate, kg N ha$^{-1}$ 34 (336)‡ | 67 (672) | 101 (1008) |
|---|---|---|---|
| | Grain N, kg ha$^{-1}$ | | |
| CT | 485§ | 548 | 585 |
| MT | 512 | 590 | 638 |
| NT | 450 | 549 | 636 |

† CT, conventional till; MT, minimum till; NT, no till.
‡ Values in ( ) = total N fertilizer applied in 12 yr.
§ $LSD_{(0.05)}$ = 29 kg N ha$^{-1}$ (compare tillage within N rate); $LSD_{(0.05)}$ = 24 kg N ha$^{-1}$ (compare N rates within tillage).

and that soil N mineralization potential was greater with NT than with CT and MT (Wienhold and Halvorson, 1999). By harvest of 1994, residual soil $NO_3$–N in the NT plots had declined to 1985 levels for all N rates in contrast to CT and MT plots. The reason for the increase in postharvest soil $NO_3$–N in 1996 compared with 1995 is not known. Perhaps the postharvest residual soil $NO_3$–N levels in 1994 and 1995 are lower than previous years because of good crop yields and $NO_3$–N leaching below 150-cm depth in the above-average precipitation years of 1993, 1994, and 1995. The residual $NO_3$–N values in 1996, a more average precipitation amount for the growing season, may reflect a level of residual $NO_3$–N in the soil profile following N fertilization that would be expected in the long term.

The tillage × N rate × year × soil depth interaction (Table 6) shows that, except for the 0- to 30-cm depth, soil $NO_3$–N levels at the deeper depths were relatively low following harvest through 1989 for all tillage and N rates. Little if any $NO_3$–N was leached below the 150-cm root zone of the 34 kg N ha$^{-1}$ rate, except in 1993. This would be expected because annual grain N removal generally exceeded the 34 kg N ha$^{-1}$ application rate. Some $NO_3$–N may have moved below the 150-cm depth in 1993 as indicated by the higher level of postharvest soil $NO_3$–N in the 120- to 150-cm depth in 1993 compared with 1992, which was probably a function of above-average rainfall in June and July of 1993 (Table 1). At the 67 and 101 kg N ha$^{-1}$ rates, the deeper soil depths remained low in $NO_3$–N until 1990. From 1991 through 1994, $NO_3$–N in the upper soil profile moved toward the lower soil depths, and the greatest quantity of $NO_3$–N movement was associated with the 101 kg N ha$^{-1}$ rate. In 1993 and 1994, some $NO_3$–N may have even moved below the 150-cm depth because the 1995 $NO_3$–N levels at the 120- to 150-cm soil depth had decreased slightly from 1994. Above-average precipitation in July of 1993 and September and October of 1994 (Table 1) contributed to the movement of $NO_3$–N to deeper soil depths and to potential loss from the root zone of this cropping system. Bauer et al. (1989) reported soil water use by SW and WW from the 150-cm soil depth in a nearby study. Sunflower in the rotation may recover $NO_3$–N below the 150-cm depth because of its deeper rooting potential. Merrill et al. (1994) reported sunflower rooting depths of 180 cm in nearby studies.

## SUMMARY

Grain N removal was a function of grain yield, which was affected by tillage system, N fertilizer rate, and year. Grain N removal was greatly decreased during the drought years of 1988, 1989, and 1990 when grain yields were low. Grain N removal generally increased with increasing N rate for all tillage treatments. Total N removed in the grain after 12 crops was lowest with NT at the 34 kg N ha$^{-1}$ rate and greatest with NT and MT at the 101 kg N ha$^{-1}$ rate.

Postharvest $NO_3$–N levels before the drought years remained fairly constant in the soil profile for all tillage and N treatments. Following the drought years, soil $NO_3$–N level increased significantly in the upper depths of the profile for all tillage and N rate treatments. Soil profile $NO_3$–N levels were generally greater with CT and MT than with NT. Soil $NO_3$–N levels had declined to 1985 levels by 1994 in all tillage systems at the 34 kg N ha$^{-1}$ rate and at the 67 and 101 kg N ha$^{-1}$ rates with NT. No N fertilization in 1991 and 1992 along with good crop yields (Halvorson et al., 1999a, 1999b, 2000) from 1991 through 1994 contributed to the decline in residual soil $NO_3$–N levels. Some soil $NO_3$–N may have also moved below the root zone in 1993 and 1994 for all

**Table 5. Postharvest $NO_3$–N in 0- to 150-cm soil profile as a function of tillage and N treatment, averaged over three crop sequences [spring wheat (SW), winter wheat (WW), and sunflower (SF)] each year in SW–WW–SF rotation at Mandan, ND (significant tillage × N rate × year interaction).**

| Tillage† | N rate | Year 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1992 | 1992 | 1993 | 1994 | 1995 | 1996 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg N ha$^{-1}$ | | | | | | | | | | | |
| CT | 34 | 32‡ | 40 | 19 | 52 | 101 | 145 | 196 | 57 | 68 | 49 | 30 | 86 |
| | 67 | 37 | 42 | 25 | 95 | 142 | 243 | 230 | 136 | 131 | 134 | 83 | 154 |
| | 101 | 58 | 56 | 59 | 124 | 147 | 393 | 362 | 253 | 215 | 281 | 111 | 247 |
| MT | 34 | 30 | 47 | 16 | 64 | 90 | 163 | 138 | 37 | 74 | 54 | 31 | 98 |
| | 67 | 29 | 38 | 30 | 76 | 124 | 206 | 172 | 158 | 170 | 84 | 45 | 134 |
| | 101 | 53 | 49 | 67 | 155 | 170 | 324 | 344 | 249 | 222 | 148 | 78 | 233 |
| NT | 34 | 39 | 41 | 12 | 56 | 55 | 63 | 76 | 15 | 39 | 20 | 15 | 88 |
| | 67 | 30 | 36 | 26 | 59 | 72 | 171 | 142 | 48 | 76 | 33 | 21 | 86 |
| | 101 | 40 | 45 | 64 | 113 | 112 | 260 | 210 | 123 | 119 | 62 | 40 | 144 |

† CT, conventional till; MT, minimum till; NT, no till.
‡ $LSD_{(0.05)}$ = 42 kg N ha$^{-1}$ (compare tillage within N rate × year); 42 kg N ha$^{-1}$ (compare N rates within tillage × year); 58 kg N ha$^{-1}$ (compare years within tillage × N rate).

**Table 6. Postharvest $NO_3$–N as a function of soil depth for each tillage and N treatment, averaged over three corp sequences [spring wheat (SW), winter wheat (WW), and sunflower (SF)] each year in SW–WW–SF rotation at Mandan, ND (significant tillage × N rate × year × soil depth interaction).**

| Tillage† | N rate | Soil depth | Year 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | kg N ha$^{-1}$ | cm | kg N ha$^{-1}$ | | | | | | | | | | | |
| CT | 34 | 0–30 | 12‡ | 11 | 9 | 36 | 73 | 91 | 91 | 9 | 13 | 11 | 14 | 25 |
| | | 30–60 | 5 | 5 | 4 | 4 | 15 | 33 | 86 | 35 | 10 | 4 | 2 | 12 |
| | | 60–90 | 4 | 6 | 2 | 3 | 4 | 6 | 7 | 7 | 21 | 2 | 1 | 13 |
| | | 90–120 | 6 | 8 | 2 | 3 | 4 | 5 | 6 | 4 | 14 | 19 | 3 | 16 |
| | | 120–150 | 6 | 9 | 3 | 6 | 5 | 10 | 6 | 2 | 10 | 13 | 11 | 20 |
| MT | 34 | 0–30 | 12 | 17 | 8 | 36 | 71 | 108 | 60 | 13 | 12 | 25 | 17 | 32 |
| | | 30–60 | 5 | 6 | 2 | 8 | 7 | 41 | 53 | 13 | 9 | 9 | 2 | 15 |
| | | 60–90 | 4 | 6 | 1 | 5 | 4 | 5 | 12 | 7 | 18 | 2 | 2 | 13 |
| | | 90–120 | 4 | 7 | 2 | 7 | 3 | 5 | 6 | 2 | 20 | 7 | 3 | 16 |
| | | 120–150 | 5 | 10 | 2 | 7 | 5 | 4 | 7 | 3 | 14 | 12 | 7 | 22 |
| NT | 34 | 0–30 | 14 | 11 | 5 | 39 | 39 | 43 | 50 | 9 | 10 | 13 | 8 | 25 |
| | | 30–60 | 5 | 6 | 2 | 5 | 6 | 7 | 7 | 1 | 7 | 2 | 2 | 15 |
| | | 60–90 | 5 | 7 | 1 | 3 | 3 | 5 | 9 | 1 | 7 | 2 | 1 | 15 |
| | | 90–120 | 8 | 11 | 1 | 4 | 3 | 4 | 6 | 1 | 7 | 2 | 2 | 16 |
| | | 120–150 | 7 | 7 | 2 | 5 | 4 | 3 | 4 | 3 | 8 | 2 | 3 | 17 |
| CT | 67 | 0–30 | 10 | 12 | 8 | 67 | 85 | 175 | 100 | 26 | 12 | 5 | 23 | 38 |
| | | 30–60 | 7 | 5 | 4 | 8 | 24 | 42 | 95 | 65 | 31 | 10 | 4 | 20 |
| | | 60–90 | 5 | 6 | 4 | 6 | 5 | 8 | 17 | 26 | 34 | 55 | 3 | 17 |
| | | 90–120 | 5 | 8 | 4 | 6 | 5 | 8 | 8 | 14 | 30 | 40 | 11 | 29 |
| | | 120–150 | 9 | 11 | 6 | 7 | 23 | 11 | 9 | 6 | 24 | 25 | 42 | 50 |
| MT | 67 | 0–30 | 9 | 13 | 12 | 55 | 88 | 143 | 66 | 26 | 16 | 9 | 22 | 49 |
| | | 30–60 | 6 | 8 | 11 | 5 | 22 | 45 | 60 | 84 | 13 | 4 | 4 | 20 |
| | | 60–90 | 4 | 5 | 3 | 6 | 5 | 7 | 25 | 29 | 42 | 4 | 3 | 14 |
| | | 90–120 | 4 | 5 | 2 | 4 | 4 | 5 | 6 | 15 | 78 | 24 | 6 | 22 |
| | | 120–150 | 6 | 7 | 3 | 5 | 5 | 7 | 15 | 4 | 21 | 43 | 10 | 29 |
| NT | 67 | 0–30 | 9 | 11 | 9 | 37 | 48 | 99 | 74 | 14 | 13 | 18 | 12 | 23 |
| | | 30–60 | 6 | 5 | 4 | 7 | 11 | 47 | 29 | 16 | 11 | 5 | 2 | 12 |
| | | 60–90 | 5 | 5 | 2 | 4 | 4 | 11 | 24 | 15 | 23 | 3 | 2 | 14 |
| | | 90–120 | 5 | 5 | 2 | 4 | 4 | 6 | 7 | 1 | 19 | 2 | 2 | 17 |
| | | 120–150 | 5 | 9 | 8 | 7 | 5 | 7 | 7 | 2 | 11 | 5 | 4 | 20 |
| CT | 101 | 0–30 | 19 | 17 | 22 | 85 | 95 | 276 | 145 | 22 | 13 | 16 | 30 | 88 |
| | | 30–60 | 16 | 9 | 14 | 10 | 29 | 75 | 155 | 110 | 16 | 12 | 5 | 30 |
| | | 60–90 | 8 | 8 | 9 | 9 | 7 | 13 | 37 | 90 | 79 | 44 | 6 | 22 |
| | | 90–120 | 7 | 11 | 8 | 10 | 7 | 15 | 12 | 25 | 77 | 98 | 23 | 38 |
| | | 120–150 | 8 | 10 | 7 | 10 | 9 | 14 | 13 | 6 | 31 | 111 | 47 | 69 |
| MT | 101 | 0–30 | 17 | 17 | 19 | 106 | 117 | 155 | 132 | 24 | 16 | 23 | 37 | 101 |
| | | 30–60 | 11 | 7 | 17 | 18 | 27 | 131 | 162 | 85 | 13 | 16 | 7 | 37 |
| | | 60–90 | 12 | 9 | 11 | 10 | 8 | 13 | 29 | 57 | 74 | 7 | 5 | 20 |
| | | 90–120 | 7 | 7 | 10 | 9 | 8 | 12 | 12 | 61 | 76 | 29 | 12 | 27 |
| | | 120–150 | 7 | 10 | 10 | 12 | 10 | 13 | 10 | 22 | 42 | 74 | 17 | 47 |
| NT | 101 | 0–30 | 14 | 13 | 13 | 65 | 66 | 118 | 62 | 16 | 16 | 31 | 21 | 50 |
| | | 30–60 | 7 | 7 | 15 | 15 | 18 | 104 | 80 | 12 | 6 | 3 | 3 | 26 |
| | | 60–90 | 6 | 6 | 9 | 9 | 8 | 17 | 35 | 53 | 9 | 2 | 3 | 22 |
| | | 90–120 | 6 | 11 | 16 | 12 | 10 | 11 | 20 | 23 | 47 | 10 | 5 | 20 |
| | | 120–150 | 6 | 9 | 11 | 12 | 11 | 11 | 14 | 18 | 40 | 17 | 8 | 26 |

† CT, conventional till; MT, minimum till; NT, no till.
‡ $LSD_{(0.05)}$ = 21 kg N ha$^{-1}$ (compare tillage within N rate × year × depth); 21 kg N ha$^{-1}$ (compare N rate within tillage × year × depth); 22 kg N ha$^{-1}$ (compare years within tillage × N rate × depth); 21 kg N ha$^{-1}$ (compare depths within tillage × N rate × year.

N rates and tillage treatments. The amount of $NO_3$–N moving below the root zone was greater within CT and MT systems compared with NT and also increased with increasing N fertilizer rate.

The results of this study show that the total amount of N removed in the grain in 12 yr was greater (144%) than that applied at the 34 kg N ha$^{-1}$ rate and less N was removed (84 and 61%) than applied at the 67 and 101 kg N ha$^{-1}$ rates, respectively. The results indicate that the long-term fertility of these soils cannot be maintained without adequate N fertilization. The NT and MT systems tended to be more efficient (63% of N applied) in grain N removal compared with CT (58% of N applied) at the highest N rate, which reflects the slightly higher grain yields with NT and MT in this study. The NT system generally had a lower level of residual soil $NO_3$–N than CT and MT systems at all N rates, which reduces the quantity of $NO_3$–N available for leaching.

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